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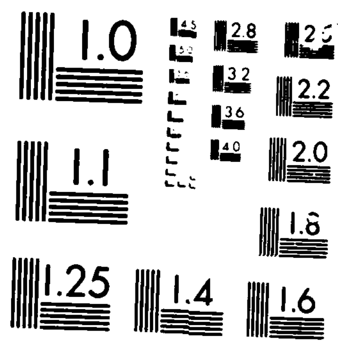

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BASIC AND APPLIED RESEARCH IN THE FIELD OF ELECTRONICS AND COMMUNICATIONS

FINAL REPORT

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Submitted by

Jonathan Allen

November 1, 1982 - October 31, 1985

U. S. Army Research Office

Contract DAAG29-83-K-0003

Research Laboratory of Electronics

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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Key Words: Atomic physics, Communications, Electromagnetics, Electronics, Lasers, Microwaves, Molecular physics, Quantum electronics, Signal processing.

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SUMMARY OF RESEARCH

I. Picosecond Optical Devices
(Professors H. Haus, E. Ippen, and J. Fujimoto [appointed Assistant Professor, January 1, 1985])

During this period, considerable progress was made on experimental and theoretical designs for optical waveguide switches, multiplexors, and demultiplexors that can operate at a rate of 20 gigahertz, centered around the waveguide Mach-Zehnder interferometer. Extensive investigations into device applications of coupled waveguide structures have led to the ability to inject power into one of n input waveguide ports, and deliver power from any selected port using these techniques. Basic logic gates have been formed, building the interferometer in gallium arsenide, and simple exclusive OR gates have been demonstrated.

Quantum noise in phase locked laser oscillators was studied, with the goal of using light that produces noise levels less than shot noise, and hence, is in a "squeezed state." Oscillations in this mode have been successfully demonstrated.

During this contract, a femtosecond laser facility was built which led to the achievement of optical pulses as short as 16 femtoseconds, with a center wavelength of approximately 625 nanometers, comprised of only eight optical cycles. This capability has led to several applications, including the observation of nonequilibrium electron temperatures in a metal, and the direct excitation and observation of optical phonon oscillations in a molecular crystal. Using molecular beam epitaxy techniques, quantum well and multiple quantum well lasers are now being made. Also during this period, a theory for soliton lasers was developed.

References: 11, 13, 15, 17, 19, 24, 25, 43, 44, 45, 47, 80, 81, 87, 112, 140, 160, 161).

II. Picosecond Dye Laser Optics
(Professor M. Salour [terminated from M.I.T. on December 10, 1982; hence his participation in this three-year contract was limited to five weeks])

During this contract period, the modelocking of optically-pumped semiconductor lasers was developed at a wavelength of 1.25μ, with six milliwatts cw power, which led to pulses 5.8 picoseconds long.

(References: 16, 17, 18, 19, 20, 23, 24, 25, 43, 44, 45, 47, 68, 77, 78, 79, 80, 81, 82, 83, 87, 110, 119, 120, 135, 136, 143, 146, 153, 154, 160, 163).

III. Chemical Reaction Dynamics on Semiconductor Surfaces
(Professor S. Ceyer)

During the contract period, an extensive apparatus for studying molecular beam surface reactive scattering was developed. In this apparatus, fluorine, chlorine, and oxygen atoms are directed at silicon and gallium arsenide surfaces. A mass spectrometer is then used to determine the identities of the reaction products, and to probe the mechanisms and dynamics of the

atom-surface reaction. A very large and elaborate apparatus has been successfully constructed, and experiments probing these surface reactions are now underway.

IV. Picosecond Spectroscopy of Phase Transitions in Solids
(Professor K. Nelson)

In this project, the dynamics of cooperative motion in crystals near structural phase transitions was studied through the use of a novel, nonlinear optical technique based on picosecond laser pulses. These pulses literally move atoms or molecules inside a crystal from their initial positions. This technique leads to fast, efficient optical switching and modulation, and takes advantage of the strong divergences of useful optical properties near some phase transitions. It has also been extremely useful in measuring the dynamics and interactions of acoustic and other low-frequency modes. Light-by-light modulation and switching by using these techniques is currently under development.

V. Optical Spectroscopy of Disordered Materials
(Professor J. D. Litster)

In this unit, partially ordered liquids and partially disordered solids have been studied. The emphasis has been on surfactant solutions that manifest interesting combinations of short- and long-range orientational and positional order under varying experimental conditions. These studies have led to new understandings, both theoretical and experimental, of partially ordered systems. They have also led to new work on colloidal crystals as model systems to investigate epitaxial growth. Because the lattice parameter of the colloidal crystals is several thousand Å, the substrate pattern can be controlled on an effectively atomic scale.

(Reference: 107).

VI. Quantum Transport in Low-Dimensional Disordered Systems
(Professor P. A. Lee)

When a channel width of silicon MOSFETs is less than 1,000Å, and the channel length is several microns long, irregular structures in the channel resistance as a function of gate voltage are observed. During this contract, a new model for one-dimensional variable range hopping has been util zed to explain all of these effects. Furthermore, the work has led to the exciting possibility of observing the properties of a single, quantum mechanical state in a conductivity measurement. Interestingly, the hopping conduction mode in quasi-one-dimensional systems is not found to be self-averaging in the sense that the resistance fluctuations average away in a limit of an infinitely long channel length. Once again, these results have been elegantly explained in a theoretic manner.

(References: 46, 48).

VII. High Resolution X-Ray Diffuse Scattering
(Professor R. J. Birgeneau)

During this contract period, a major investment was made to develop synchrotron x-ray techniques and facilities, although these were not completed during the contract period. Instead, emphasis was placed on partially ordered systems, including intercalation compound structures and transitions. In particular, layers of bromine inserted in a lamellar material such as graphite were studied, and several orientation patterns on either side of the commensurate-incommensurate transition were observed and characterized theoretically. In addition, krypton physisorbed onto graphite provided examples of two-dimensional freezing and of transitions driven by competing effects. Finally, a new understanding of critical phenomena associated with the transitions from the nematic phase to smectic A and smectic C phases of liquid crystal materials was realized.

(References: 12, 14, 42, 54, 58, 59, 62, 69, 84, 104, 108, 122, 123, 139, 151).

VIII. Excitations, Ground State Properties, and Phase Transitions of Surfaces
(Professor J. Joannopoulos)

During this period, a simple and tractable scheme to derive the force constants of a material was devised. This led to the ability to predict the bulk phonons in SiC throughout the entire brillouin zone, and to determine the change in force constraints due to atomic relaxations around a carbon vacancy. Furthermore, the surface phonons on the Si(100) surface were predicted. This comprised the first realistic calculation of phonons on a semiconductor surface. The deposition of aluminum atoms on GaAs(110) was also studied by predicting the lowest energy stable configurations by minimizing the system's total energy with respect to its structural degrees of freedom. This led to an energy contour map that described in detail the interaction energy of an atom with a zero temperature surface. Many interesting effects were found, including aluminum puddles found to have lower energy than chemisorbed aluminum atoms. These techniques were extended to finite temperature by combining total energy calculations based on microscopic electronic structure with position-space renormalization-group calculations used to predict structural phase transitions as a function of temperature. Experimental measurements have agreed with these highly-detailed theoretical predictions.

(References: 33, 34, 90, 148).

IX. Phase Transitions in Chemisorbed Systems
(Professor A. N. Berker)

The goal of this work has been to derive material properties by treating the many-body interactions between the microscopic components in a manner that can be experimentally confirmed. The most stringent tests of such a theoretical program occur at phase transitions, since the correlated motions of a very large number of microscopic variables come into play. A major tool for this work has been the renormalization group transformation which has been used to study several systems including the phase diagram of oxygen on Ni(100). In particular, the possibility of two distinct 2x2 overlayer phases was predicted, thus enriching the theoretical understanding of these surface phenomena. The effect of criticality on wetting layers was also studied, and the Potts spin models were utilized as a theoretical tool to study phase

transitions.

(References: 1, 2, 5, 7, 8, 21, 36, 37, 38, 39, 40, 41, 56, 57, 95, 100, 103, 109, 116, 129, 130, 147, 164).

X. Electronic Properties of Amorphous SiO_2 and Related Glasses (Professor M. A. Kastner)

In this work, defects in amorphous SiO_2 were studied by using a fluorine laser which was used to excite photoluminescence. By using the same apparatus, photo-induced paramagnetism was achieved, and the spin signals of at least five specific defects were isolated. When hydrogen is present in the glass, however, the density of photo-induced spins is drastically reduced.

During this contract period, work started on the experimental characterization of conductance variations in narrow gate MOSFETs. These variations can be as large as a factor of 10^3 at $4^{o}K$. Several interesting effects have been discovered, and theoretically characterized by Professor P. A. Lee. These include the fact that the current depends exponentially on the drain-to-source voltage V_{DS} when the conductance is small. Under these conditions, there is rectification so that the device behaves in a way that is microscopically asymmetric although it is macroscopically symmetric. It is believed that the fluctuations in resistance from changes in the gate voltage and magnetic field are an example of quantum interference effect predicted for all disordered conductors by Professor Lee's theory.

(References: 46, 50, 71, 72, 106, 124, 125, 138, 149, 152).

XI. Coherent Atom-Field Interactions in Vapors with Applications to New Time Standards (Professor S. Ezekiel)

High-resolution studies have been performed on the interaction of one and two monochromatic laser fields with prepared two- and three-level systems in an atomic beam of sodium. Several basic, experimental measurements have been made, providing fundamental information about the nature of atom field interaction which can be directly related to theoretical predictions. A preliminary investigation of a clock's performance based on a laser-induced resonance Raman transition in an atomic beam has been completed. This has led to a clock stability of 1.5×10^{-11} for a 1,000-second averaging time. This stability is near the shot noise limit for the present arrangement.

XII. Basic Studies in Solid State Resonator Gyroscopes (Professor S. Ezekiel)

The use of the Sagnac effect has been studied for the development of sensors of absolute rotation (i. e., optical gyroscopes based on passive rather than active techniques). Nonlinear index effects resulting in nonreciprocity have been studied, and the overall performance has been close to the shot noise limit. In addition, Fresnel drag has been measured, thus assessing the contribution of index and dispersion leading to special relativity effects in moving media.

(References: 35, 51, 60, 74, 88, 89, 93, 96, 97, 98, 117, 118, 126, 127, 137, 141, 145).

XIII. Electrodynamics in a Cavity
(Professor D. Kleppner)

In this unit Rydberg atoms are used to study cavity quantum electrodynamics. The major focus has been on the inhibition of spontaneous emission, which represents the fundamental interaction of matter with a vacuum, and is generally regarded as an irreversible process of nature. In addition, spontaneous emission is the ultimate noise source in any quantum measurement. Until recently, spontaneous emission was treated as an unalterable fact of nature. But, by altering the modes of the vacuum (e. g., by using a high-Q cavity), the spontaneous emission rate can be modified. This effect has been demonstrated by essentially turning off spontaneous emission for atoms travelling between parallel plates. The effect is dramatic; the spontaneous emission rate changes abruptly from its normal free value space to a value so close to zero that it cannot be measured in contemporary practice. These results have profound implications on noise in ultra-high resolution electronic systems.

(References: 31, 32, 132, 133).

XIV. Submicron Structures Technology and Applications
(Professors H. I. Smith, M. A. Kastner, D. Antoniadis, and Dr. J. Melngailis)

Through JSEP support, the technology for fabricating submicron structures and their application in a variety of research projects has been provided. Dimensional control at the 100Å level has been provided, and lateral surface superlattices in a silicon MOSFET configuration have been fabricated. These have led to new studies of quantum transport effects. For example, it was learned that the grating period in the superlattices does not have to be less than the elastic scattering length (approximately 200Å in silicon) because the elastic scattering maintains phase coherence, and does not inhibit the observation of Bragg reflection from the potential modulation imposed by the grating gate. These results are encouraging for the further investigation of quantum effect devices. MOSFETs with channels as short as 600Å have been fabricated. These are the world's smallest, and they have been extensively characterized, leading to the first observation of velocity overshoot in silicon. This fabrication technology has also been used to build MOSFETs with channels less than 1,000Å wide, which have been used to study conductance modulation effects at low temperature in essentially one-dimensional MOSFETs. New theories of conduction have been constructed to support these experimental results.

(References: 3, 9, 26, 27, 28, 29, 30, 46, 49, 50, 63, 68, 76, 85, 86, 97, 111, 114, 131, 155, 157, 159).

XV. Electromagnetic Waves
(Professor J. Kong)

A wide variety of theoretical studies of microstrip antennas and microwave integrated circuits were completed. Frequency domain techniques are now being applied to the study of coupling and transmission of electromagnetic waves in microelectronic integrated circuitry. Another important contribution of this work was the study of the characteristics and existence of focused

wave modes in the time domain. The understanding of this is crucial for the generation of high-power concentrations in space. These techniques have also been used in studying transient electromagnetic analysis in the presence of multi-layered integrated circuits. In addition, the propagation and scattering of electromagnetic waves by anisotropic media has been studied.

(References: 10, 22, 64, 65, 66, 67, 162).

XVI. Localized Magnetostatic Resonance and Wave Propagation
(Professor R. Morgenthaler)

In this unit, the goal was to develop coherent magnetic wave signal processing techniques for microwave energy which could either be used as the primary signal or the intermediate frequency modulation of millimeter wavelength signals. Quasi-optical propagation of electromagnetic and magnetostatic waves was used in high-quality, single-crystal ferrite thin films. Both experimental and theoretical analyses verified several new transmission modes, and sensitive probe techniques were realized. Furthermore, bias techniques which allow a great deal of control over mode energy distributions can be exercised by the proper choice of gradients, thus providing the basis for new forms of microwave signal processors.

(References: 6, 70, 75, 92, 99, 113, 142).

XVII. Atomic Probes of Structure and Energy Transfer
(Professor D. Pritchard)

During this contract, extensive studies on atom-molecule collisions at low temperatures were completed, illustrating that the collision mechanism at low temperatures is strongly altered by long-range attractive forces. In addition, a new design for trapping neutral atoms and cooling them to micro-K temperatures was developed. Work also began on new, experimental apparatus for precision mass comparison using single-ion cyclotron resonance. Such apparatus will require a detector which is successfully capable of measuring 10^{-14}-amp current at 160 kilohertz.

(References: 52, 61, 134).

XVIII. Control of Microstructure in Thin-Film Electronic Materials
(Professor C. Thompson [joined JSEP program on July 1, 1983])

The goal of this work was to develop a new understanding that will lead to the control of microstructure in thin metallic films. In particular, new techniques for creating very large grains in aluminum interconnect lines (larger than 100 microns) have been demonstrated by creating a sandwich of copper and chromium between two outer layers of aluminum. Such large grain sizes are highly resistant to electromigration effects, and can be coupled with techniques that can arrange grain boundaries perpendicular to the current flow, thus providing an even further advantage.

(Reference: 115).

PERSONNEL SUPPORTED BY THE JOINT SERVICES ELECTRONICS PROGRAM

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J. G. Fujimoto
H. A. Haus
E. P. Ippen
J. D. Joannopoulos
D. Kleppner
J.-A. Kong
P. A. Lee
J. D. Litster
M. A. Kastner
J. Melngailis
F. R. Morgenthaler
K. A. Nelson
D. Pritchard
M. M. Salour
H. I. Smith
C. V. Thompson

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P. R. Hemmer
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A. Lattes
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V. Pevtchin
I. Plotnik
S. Y. Poh
R. Ponikvar
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M. G. Prentiss
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H. M. Quek
H. Raumer
C. M. Rappaport
D. Rennie
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A. Rosenberg
G. A. Sanders
M. L. Schattenburg
S. C. Schott
M. T. Schulberg
A. Sezginer
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G. G. Shahidi
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R. J. Simonson
E. Specht
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J. H. Stathis
J. A. Stein
D. A. Summa
M. Sutton
G. Szuba
S. L. Tang
R. E. Tench
L. Tsang
M. Tsuk
A. N. Tulintseff
N. P. Vlannes
J. S. Walker
H.-Z. Wang
J. R. Wang
A. Weiner
J. J. Xiong
X. Xu
K. Yamaguchi
Q. Y. Yang
Y. E. Yang
A. Yen
J. Yorsz
E. Young
F. Zarinetchi
J. Zayhowski
D. A. Zeskind
D. Zion
M. A. Zuniga

DEGREES AWARDED UNDER JOINT SERVICES SUPPORT
November 1, 1982 - October 31, 1985
Contract DAAG 29-83-K-0003

I. Picosecond Optical Devices

J. G. Fujimoto, Ph.D., 1984
C. Gabriel, Ph.D., 1985
M. N. Islam, Ph.D., 1983
M. Kuznetsov, S.M., 1982
A. Lattes, Ph.D., 1983
L. Molter-Orr, S.M., 1983
R. Putnam, Ph.D., 1983
A. Weiner, Ph.D., 1984
J. Yorsz, S.M., 1983

II. Picosecond Dye Laser Optics

No degrees granted.

III. Chemical Reaction Dynamics on Semiconductor Surfaces

S. L. Tang, Ph.D., 1985

IV. Picosecond Spectroscopy of Phase Transitions in Solids

No degrees granted.

V. Optical Spectroscopy of Disordered Materials

No degrees granted.

VI. Quantum Transport in Low-Dimensional Disordered Systems

No degrees granted.

VII. High Resolution X-Ray Diffuse Scattering

A. Erbil, Ph.D., 1983
L. J. Martinez-Miranda, Ph.D., 1985
B. M. Ocko, Ph.D., 1984
P. A. Heiney, Ph.D., 1982
S. G. J. Mochrie, Ph.D., 1985

VIII. Excitations, Ground State Properties, and Phase Transitions of Surfaces

D. H. Lee, Ph.D., 1982

IX. Phase Transitions in Chemisorbed Systems

D. Andelman, Ph.D., 1984
R. G. Caflisch, Ph.D, 1984
M. Kardar, Ph.D., 1984

R. E. Goldstein, S. B., 1983
S. I. Chase, S. B., 1985

X. Electronic Properties in Amorphous SiO_2 and Related Gasses

J. H. Stathis, Ph.D.
R. F. Kwasnick, Ph.D

XI. Coherent Atom-Field Interactions in Vapors Applications to New Time Standards

XII. Basic Studies in Solid State Resonator Gyroscopes

G. A. Sanders, Ph.D., 1983
B. W. Peuse, Ph.D., 1983
D. R. Ponikvar, Ph.D., 1983
P. R. Hemmer, Ph.D., 1984
R. E. Tench, Ph.D., 1985
D. J. DiFilippo, S.M., 1984
F. H. Long, S.B./S.M., 1985
G. P. Ontai, S.M., 1985
S. K. Jain, S.M., 1985
A. Rosenberg, S.B., 1984
A. G. Osler, S.B., 1984
K. Yamaguchi, S.B., 1984
M. D. Battat, S.B., 1985

XIII. Electrodynamics in a Cavity

R. Hulet, Ph.D., 1984
L. Brewer, Ph.D., 1984

XIV. Submicron Structures Technology and Applications

E. H. Anderson, S.M., 1984
H. J. Lezec, S.M., 1984
M. L. Schattenburg, Ph.D., 1984
R. F. Kwasnik, Ph.D., 1984
I. Plotnik, S.M., 1985
G. G. Shahidi, S.M., 1984
A. C. Warren, Ph.D., 1985
K. A. Bezjian, Ph.D., 1985
H. A. Atwater, S.M., 1983
C. J. Keavney, S.M., 1983
J. E. Palmer, S.M., 1985
S. S. Dana, Ph.D., 1983
L. F. A. Mougel, S.M., 1984
J. M. A. Palella, S.M., 1984
J. A. Stein, Ph.D., 1985
D. A. Summa, S.M., 1985
S. C. Schott, S.M., 1985

XV. Electromagnetic Waves

S.-L. Chuang, Ph.D., 1983
T. M. Habashy, Ph.D., 1983
R. T. Shin, Ph.D., 1984
Y. Jin, Ph.D., 1985
J. K. Lee, Ph.D., 1985
Abdurrahman Sezginer, Ph.D., 1985
Apo Sezginer, S.M., 1982
C. M. Rappaport, S.M., 1982
S. L. Lin, S.M., 1983
H. Cheung, S.M., 1984
G. Szuba, S.M., 1984
D. Park, S.M., 1984; S.B., 1982
F. C. Lin, S.M., 1984
A. N. Tulintseff, S.M., 1985
J. Kiang, S.M., 1985
Y. E. Yang, S.M., 1985
R. Y. Kim, S.B., 1983
D. Zion, S.B., 1984
L. C. Howard, S.B., 1984

XVI. Localized Magnetostatic Resonance and Wave Propagation

N. P. Vlannes, Ph.D., 1984
M. Borgeaud, S.M., 1984

XVII. Atomic Probes of Structure and Energy Transfer

A. Migdall, Ph.D., 1985

XVIII. Control of Microstructure in Thin-Film Electronic Materials

No degrees awarded.

PUBLICATIONS ACKNOWLEDGING JOINT SERVICES SUPPORT

Published, Accepted for Publication, or Submitted

1 November 1982 - 31 October 1985

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Papers Published

1. D. Andelman and A. Aharony, "Critical Behavior with Axially Correlated Random Bonds," Phys. Rev. B 31:7, 4305-4312 (1985)

2. D. Andelman and J. S. Walker, "Preserving the Free Energy in a Migdall-Kadanoff Approximation for the q-State Potts Model," Phys. Rev B 27:1, 241-247 (1983)

3. E. H. Anderson, C. M. Horwitz, and H. I. Smith, "Holographic Lithography with Thick Photoresist," Appl. Phys. Lett. 43:9, 874-875 (1983)

4. R. J. Birgeneau, C. W. Garland, A. R. Kortan, J. D. Litster, M. Meichle, B. M. Ocko, C. Rosenblatt, L. J. Yu, and J. Goodby, " Smectic-A-Smectic-C Transition: Mean Field or Critical," Phys. Rev. A 27:2, 1251-1254 (1983)

5. Blankschtein, Y. Shapir, and A. Aharony, "Potts Models in Random Fields," Phys. Rev. B 29:3, 1263-1267 (1984)

6. M. Borgeaud and F. R. Morgenthaler, "An Improved Two-Port Magnetoelastic Delay Line," IEEE Trans. Vol. MAG-21, No. 2, pp. 1156-1163, March 1985

7. R. G. Caflisch and A. N. Berker, "Oxygen Chemisorbed on Ni(100): A Renormalization-Group Study of the Global Phase Diagram," Phys. Rev. B 29:3, 1279-1286 (1984)

8. S. I. Chase and M. Kaufman, "Renormalization-Group Analysis of Heath Capacity Critical Amplitudes," Phys. Rev. B 33:1, 239-244 (1986)

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100. A. N. Berker, Global Phase Diagrams with Order-Disorder and Structural Transitions; Renormalization-Group Approach (invited paper)

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109. R. E. Goldstein, Molecular Structure and Hydrogen Bonding at Lower Critical Solution Points

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145. S-T. Ho, S. Ezekiel, J. R. Haavisto, and J. J. Danko, Optical Feedback Phase-Autolocking of a Semiconductor Laser (pp. 134-135)

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147. D. Andelman, M. Kardar, and M. Kaufman, Divergences and Zeroes of Critical Amplitudes (p. 372)

148. E. Kaxiras, Y. Bar-Yam, and J. D. Joannopoulos, The Reconstruction of the (111) Polar Surface of GaAs (p. 313)

149. J. Licini, M. Kastner and D. J. Bishop, Negative Magnetoresistance of Quasi-One Dimensional Silicon MOSFETS (p. 483)

150. S. G. J. Mochrie, Algebraic Decay States of Two Dimensions (p. 345)

151. L. Salamanca-Riba, J. M. Gibson, G. Roth, A. R. Kortan, G. Dresselhaus, and R. J. Birgeneau, Electron Beam Induced Commensurate to Glass Phase Transition on $SbCl_5$--GIC (p. 240)

152. J. H. Stathis and M. A. Kastner, Annealing of Photoinduced Defects in Amorphous SiO_2 (p. 235)

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154. E. P. Ippen and J. G. Fujimoto, Applications of Femtosecond Optics (p. 38)

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155. S. Y. Chou, H. I. Smith, and D. A. Antoniadis, Sub-100-nm Channel Length Transistors Fabricated Using X-Ray Lithography

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160. M. Kuznetsov, D. Z. Tsang, J. N. Walpole, Z. L. Liau, and E. P. Ippen, Chaotic Pulsation of Semiconductor Lasers with a Proton-Bombarded Segment (paper TUD5:1 -- TUD:5:3)

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162. F. C. Lin, J. K. Lee, and J. A. Kong, Radar Backscattering from Snow-Covered Ice (p. 17)

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163. H. A. Haus, N. A. Whitaker, Jr., and M. C. Gabriel, All-Optical Logic Devices Using Group III-V Semiconductor Waveguides

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